Marine Resource Economics, Volume 19, pp. 7–19
Printed in the U.S.A. All rights reserved
0738-1360/00 $3.00 + .00

Spatial Management of Fisheries

JAMES E. WILEN
University of California, Davis

Abstract *This paper discusses recent advancements in scientific understanding about the spatial distribution of abundance in the ocean and the processes that determine abundance. Some discussion of the role of monitoring and information technology is presented, and examples of new findings are given. New findings run the gamut from slow processes operating over large spatial scales to episodic events operating locally over small scales. The implications of this new understanding are explored, focusing particularly on new theories of the role that oceanographic processes play in distributing larvae, juveniles, and adults into the coastal environment. A new spatial management paradigm is envisioned whereby electronic vessel and gear monitoring allows management of effort at fine temporal and spatial scales. The research challenges of this new vision of future management are then discussed, focusing on understanding spatial behavior of fishermen, developing integrated spatial bioeconomic management models, and exploring alternative management instruments for regulating the spatial distribution of harvesting.*

Key words Fisheries, management, spatial.

JEL Classification Code Q2.

Introduction

Most fisheries management systems have historically managed individual populations over either the entire geographic range of the population, or a smaller regulatory jurisdiction associated with a political boundary. The boundaries of typical management regimes have thus been relatively large, often either with homogeneous regulations applied over the whole range of the population, or with some spatial differentiation designed to counter concentration of fishing effort in various "hotspots." This somewhat *ad hoc* approach to fine-tuning regulations over space largely reflects the underdeveloped state of knowledge of marine ecosystems that managers have had to work with in the past. However, over the past decade or so, there have been improvements in fine-scale monitoring of species abundance and oceanographic processes thought to determine spatial abundance. As a result, ecologists have begun to understand more about the manner in which populations are spatially distributed over ocean environments and the mechanisms that determine this distribution.

These improvements in the ability to monitor spatial abundance in ocean systems, as well as improved understanding of the mechanisms generating spatial abundance, are surely going to lead to new demands on management systems. This is partly because as scientists learn more about where fish are concentrated and why, fishermen are also learning how to locate fine-scale fish aggregations more easily.

James E. Wilen is a professor in the Department of Agricultural and Resource Economics, University of California, Davis, Davis, CA 95616 USA, email: wilen@primal.ucdavis.edu.

Fishermen have always been well aware of the patchy nature of abundance, of course. What has changed recently is that the technology for finding fish is getting increasingly more sophisticated, creating more pressure on managers to keep up with the correspondingly increasing catching efficiency. Therefore, it is paradoxically likely that the accelerating scientific understanding of how the ocean works will bring the "race to fish" to a new level. With more concentrated and more effective local fishing mortality, managers will ultimately be forced to respond in kind by developing new explicitly spatial management policies.

This paper will explore some of these new management challenges by assessing what we currently understand about spatial management options and what we need to know in order to begin designing new tools. In the following section, we elaborate on recent developments in fisheries management science and the new paradigms that are crystallizing as a result of new understanding. The third section discusses a future vision of fisheries management that is more explicitly spatial in the application of policy instruments. The fourth section discusses the research implications of this potential new fisheries management regime and surveys what we know about critical questions of interest. The final section summarizes and concludes.

Trends in Fisheries Management Science

Fisheries management science is a relatively new discipline, with core concepts that date back to the important post-World War II work of Beverton and Holt (1957) and Ricker (1954). Their work described how fundamental processes such as recruitment, individual growth rates, natural mortality and fishing mortality, gear selectivity, and fecundity determine the dynamics of exploited fish populations. They also developed important population dynamics concepts such as stock/recruitment relationships, Ricker curves, eumetric yield, and descriptions of multiple-cohort equilibria. In addition, their work introduced and rigorously defined important new management concepts, such as maximum sustainable yield.

Since the expansion of jurisdiction in the late 1970s, managers have not been particularly successful applying the sophisticated theories developed by Beverton and Holt and Ricker to real-world management of fisheries. In hindsight, this is not surprising for several reasons. First, as recent evidence about the patchiness of populations has made clear, there has always been an important aggregation problem at work in population modeling. Most fish populations are not uniformly distributed, homogeneous whole populations as implicit in the early population modeling literature, but instead heterogeneous subpopulations with life history parameters that often differ over space and time. Thus, attempting to predict the behavior of a fictional homogeneous and "spaceless" population is likely to be compromised by the heterogeneity in real systems. Second, while early modelers purposefully focused on simplified deterministic models, real fisheries systems are plagued with high variability, poor understanding of fundamental mechanisms, and inability to statistically identify parameters of interest. A hopeful trend is that new understanding of ocean processes is beginning to illuminate more of the mechanisms by which oceanographic shocks are transmitted to various populations. Still, there is often too much noise in time series data of fisheries aggregates to effectively identify signals and estimate parameters of forecasting models. Finally, new understanding about the role of oceanographic factors as linking mechanisms suggests that systems of linked subpopulations may behave qualitatively differently from simple additive aggregations of subpopulations because of non-convexities and returns to scale in the system as a whole. For all of these reasons, the sophisticated fisheries science tools based on whole population models have failed to produce predictions that managers have enough confidence in to use to guide management decisions. As a result, we have a paradoxical situation of a relatively sophisticated body of fisheries management science, most of which is ultimately set aside for rules of thumb, on-line monitoring of indirect indicators of the health of the population, and other *ad hoc* uses of information.

While managers working with real-world fisheries have struggled with the older (and admittedly artificial) homogeneous and “spaceless” view of whole populations, marine ecologists and biologists have begun to craft a new view of marine ecosystems. This new view depicts populations as comprised of sub-populations or metapopulations distributed heterogeneously in ways that are determined by inter- and intra-species competition, the inherent productivity of the local benthic environment, and oceanographic forces that govern the mixing and transport of adults and the dispersal of larvae. Much of this new “space-rich” view has emerged out of findings from the deployment of new technology of monitoring and measurement and information processing. This new technology, in turn, has been deployed not to study fisheries per se, but for military and commercial purposes unrelated to fisheries. For example, current capabilities to map and real-time monitor surface-level oceanographic processes such as El Niños and La Niñas have emerged from remote sensing, satellite imagery, and geographical positioning systems (GPS). These geo-scale monitoring systems are largely spinoffs from technology development associated with defense spending for the purpose of monitoring for military objectives. Similarly, real-time monitoring of currents, sea surface height, upwelling and advection using coastal radar systems, acoustic Dopler systems, and moored sensors have been made possible by technology deployed to predict weather patterns. Finally, much of our understanding of fine-scale characteristics of the ocean floor has come about using side-scan radar, sediment cores, remote vehicle sensing, and other technologies developed to map and exploit sea bed minerals.

Regardless of the original purpose of recent monitoring efforts, the result of such effort has been a rapidly changing and new understanding of what is on and under the surface of the ocean and how various processes affect the distribution of life. Most important is new understanding that the ocean is a profoundly patchy medium, with resource abundance distributed in clumps rather than homogeneously. The locations of these patches of abundance are now understood to be determined partly by the inherent productivity of different kinds of substrate, and also by oceanographic linkages such as currents, wind, and sea surface height changes that influence the geographic location of upwelling and nutrient distribution. Studies show, for example, that species are more abundant near the “edges” of their ranges rather than in the centers of their ranges. These edges, in turn, are defined by places where major current systems either meet or change direction.

Within the biogeographical ranges of various species, researchers are also discovering short- and long-term mechanisms that determine the temporal variation in abundance. Some processes operate over very large-scale areas and long time scales. For example, the so-called Pacific Decadal Oscillation (PDO) appears to be a 20 to 30-year pattern in temperatures and wind stress/direction over the Pacific Ocean. This large-scale phenomenon intensifies upwelling in some regions and reduces it in other regions, altering whole assemblages of fish and elements of trophic systems for decades. The PDO operates in conjunction with, and perhaps as a determinant of, the now familiar but shorter-term phenomena called El Niños and La Niñas that impact smaller regions over yearly time scales. El Niños and La Niñas also impact upwelling and nutrient production, and they dramatically affect larval and juvenile survival and adult condition.

One of the most important arenas of new understanding concerns the manner in which shorter-term oceanographic forces determine how larvae and juveniles get distributed into various patches of abundance within the coastal environment. Many species produce larvae and juveniles that spend up to several months drifting in offshore currents at distances up to several hundred kilometers. New understanding of transport patterns off the Pacific Coast show that normal patterns of predominantly northwesterly winds during spring and summer push larvae into warm offshore gyres and eddies, at the same time inducing upwelling to bring nutrient rich cold waters near-shore. Then, as winds weaken, so-called relaxation events distribute the larvae shoreward. The settlement success of some species appears tied to upwelling events, whereas other species appear tied to relaxation events, both of which can last on the order of days. These studies show that both coastal geography and short-term weather events drive coastal circulation patterns, such as eddies and tidal bores, that seems important to larval dispersal and adult abundance. Both of these fundamental oceanographic processes cause and are determined by complex interactions between the oceans and the atmosphere, interactions with time scales that span the spectrum from local and short-term processes on the order of days or weeks to long-term and global-scale processes that operate over decades.

Future Visions of Fisheries Management

What are the fisheries management implications of these unfolding new views of marine ecosystems brought on by technological developments in monitoring, measurement, and information processing? First, we are gradually learning more about slow macro scale processes that determine how species and populations are distributed over space over large scales. In the future, we will have advanced warning of large-scale PDO-like reversals that signal dramatic changes in abundance of whole complexes of species. These long-term forecasts will allow advanced notice of important, major changes in abundance and needed changes in allowable harvests that may have substantial socioeconomic consequences. Second, at the individual population and species level, we are gradually illuminating some of the puzzles associated with recruitment variation. In the past, managers have relied on larval abundance surveys to signal strong and weak year-classes *ex post*. In the future, we will be able to forecast these *ex ante* as outcomes of unfolding weather events and oceanographic processes. This, too, will allow managers to have advanced warning of upcoming abundance patterns and needed changes in regulated harvests. Third, future management will obviously be much more information- and monitoring-intensive, employing real-time information about harvesting capabilities, biomass forecasts, and fundamental oceanographic forcing processes. These new information- and monitoring-intensive processes will capitalize on the same technology that is leading the way to better fundamental understanding of systems that have only been loosely understood in the past.

As discussed in the introduction, as scientists deploy new technology and learn more about the actual fine-scale distribution of fish resources and the mechanisms governing that distribution, so will fishermen. Fishermen have always employed personal logbooks, folk knowledge, information sharing groups, and other informal methods to track and monitor the relative spatial abundance of target species. Modern fishermen are adding satellite and weather buoy data to track temperature gradients and find fish aggregations, just as meteorologists, weather forecasters, and oceanographers use it to forecast and understand fundamental ocean and weather systems. Fishermen use GIS systems today to locate and monitor gear sets and tracking and information processing systems to monitor the success of various spatial fishing strategies, just as the information-driven economy makes use of the same technologies for a myriad of other purposes. The implication is that many fish populations that have been historically buffered by our ignorance of the ocean are now more vulnerable to overharvesting as an indirect result of accumulating knowledge of the ocean and its processes.

Thus, the likely scenario in the not too distant future is one in which information about a complex and dynamic spatial system is available to both fishermen and managers on a real-time basis. As harvesters become more efficient at locating sedentary concentrations of fish sub-populations and more responsive and able to quickly locate ephemeral abundance aggregations, regulators will have to adapt by developing new kinds of policy instruments that control fishing mortality at fine temporal and spatial scales. What will distinguish future scenarios from the present will be a movement away from whole-population focused management to sub-population focused management, and the division of management space into smaller units, or the “patches” of metapopulation models. These, in turn, will have to be managed on a fine temporal scale, with new, sophisticated enforcement and monitoring systems.

Much of the technology necessary to implement new and more sophisticated spatially explicit management schemes is available at this time. For decades economists have pointed out the need for and the difficulties associated with actually “fencing the ocean” in order to manage marine resources with the same effectiveness of some terrestrial management systems. But while it is still infeasible to physically fence the ocean, it is becoming increasingly feasible to contemplate electronically fencing the ocean. We currently have the ability to track and monitor the activities of every fishing vessel in operation on a real-time basis and with spatial accuracy down to mere inches. So it would be possible, even now, to set up an electronic zoning system that would monitor, regulate, and enforce fine-scale species and patch-specific harvesting. Such a system would work something as follows. In this (not too distant) futuristic scenario, each vessel would hold an “electronic portfolio” of rights to fish, and this portfolio would be coded into a GPS-based monitoring system. These portfolios of rights would be precisely designated spatially and temporally and enforced with an electronic enforcement system embedded into the vessel’s positioning and gear deployment mechanisms. Thus, a particular vessel might hold rights to fish in zone A at a depth between 50 and 150 fathoms, using a midwater trawl with eight-inch mesh, during the open period March 10 to March 18. The same vessel might also hold the right to use 10 skates of halibut gear on the benthic floor of section 3 of Zone C. Another vessel might hold rights to utilize similar gear but over a different set of zones, and still another vessel might only hold rights to deploy 150 crab traps of a specified design in either of sections 5 or 7 of zone D.

The ocean could thus be electronically zoned in a three-dimensional mosaic that includes no-take zones, mixed-use zones, and rotating closures and rotating use areas. Attempts to deploy gear in closed areas or areas in which an individual does not hold rights would be blocked by the electronic enforcement system built into gear deployment mechanisms. Rights to fish could be delineated much more precisely than at present, based on fine-scale time and spatial blocks (in three dimensions), enabling precision control of both quantities and specifications of gear in such a way that manages fish mortality at a high spatial and temporal resolution. Allowable catches could be determined by high-powered algorithms that incorporate real-time information as it is monitored, update and forecast continuously, and fine-tune harvests to take advantage of connections between regions and the buffering capacity of large and linked systems. The important point is that such a future system will pay much more attention to fine-scale spatial and temporal processes that are increasingly understood to determine relative abundance over a heterogeneous marine environment.

Spatial Fisheries Management and Research Challenges

This new future vision poses many interesting new challenges to fisheries economists and fisheries scientists. At least three broad types of research are likely to prove essential to implementing future spatial fisheries management systems. First, a better understanding of the determinants of fishermen behavior is needed, particularly spatial behavior. This is important because we need to understand and predict, *ex ante*, how spatial systems with fine-scale controls will affect fishermen and exploited metapopulation systems compared with coarse-scale whole population management. And prediction can only be approached by either experimentation or simulation using understanding of determinants of current spatial responsiveness and spatial behavior. Second, a better understanding of the joint influence of economically driven effort dispersal and oceanographically driven biological dispersal is needed. These two dispersal processes seem central to the manner in which exploited spatial systems operate, but we know very little about how they jointly influence exploited population dynamics. The kind of understanding necessary will only emerge with integrated bioeconomic analysis involving collaborations between economists and population modelers. Finally, an *ex ante* assessment of the implications of various potential spatial policy options is needed. This is a task that requires some conceptual analysis to illuminate when spatially disaggregated polices are likely to pay off, how different rights mechanisms might be designed, and exactly how altering incentives with direct or indirect instruments affects a spatially exploited bioeconomic system.

Fishermen Behavior

What do we know about fishermen behavior at this point? Most of what we know is about coarse-scale, long-horizon choices that fishermen make, beginning with early work on aggregate entry/exit behavior in fisheries (Wilen 1976; Bjorndal and Conrad 1987). The lessons from studies of entry/exit behavior in fisheries are consistent with economic hypotheses that fishermen respond to profitability, as we would expect. In studies of pure open-access systems, fishermen enter when rents are positive and exit when rents are negative. Aggregate behavioral response to profits is sluggish, however, so that entry does not instantly dissipate potential rents and exit does not eliminate periods of sustained losses. Some studies have found asymmetric rates of entry and exit over a cycle of profits and losses. With fisheries, as with other empirical studies of capital dynamics, it is unclear whether observed sluggishness is structural and due to some kind of internal production adjustment costs, whether it is simply a result of complex expectations formulation mechanisms, or whether it reflects specialization of fishing capital. Most studies of entry/exit dynamics have been conducted with time series of aggregate data, and such data are unable to differentiate between different classes of hypotheses.

Economists have used individual micro-level data to study important intermediate and short-term decisions that take place from year to year. Similar results about sluggish responsiveness of the “representative fisherman” emerge in studies of intermediate-term behavior, such as the analysis of target species and gear selection between seasons by Bockstael and Opaluch (1983). They find that, on average, the representative fisherman reacts to expected profits (and negatively to risk), and they find inertia or sluggish adjustment between species/gear combinations from year to year. As with other studies of intermediate- and long-term decisions, Bockstael and Opaluch (1983) use current profits and variance of profits as proxies for the present value of expected profits and/or other forward-looking representations of expected risk. To my knowledge, no fisheries studies have had actual data on expectations and outlooks gathered from independent sources or surveys. An important issue in modeling behavior is whether the representative decisionmaker framework masks important behavioral detail or portrays a heterogeneous process in an unrealistically homogeneous fashion. For example, one study of fishermen investment behavior used a panel of micro-level data on vessel upgrades gathered from accounting firms that served fishermen (Lane 1988). In that study, the author found that vessel investments were heterogeneous, discrete, and lumpy and not easily aggregated with the typical "representative fisherman" assumption.

Studies of individual micro-level behavior at finer time and spatial scales often take advantage of larger data sets and, hence, have the luxury of exploring heterogeneity of behavior. Many of these show similar responsiveness to proxies for expected profits, often with considerable heterogeneity in behavior exhibited. In one of the first empirical studies of spatial behavior, Hilborn and Ledbetter (1979) found that a British Columbia purse seine salmon fleet was composed of a profit-responsive mobile fleet and a sedentary fleet. In a study of weekly location choices, they found that the mobile fleet adjusted rapidly to changes in catch per unit effort over space, whereas the sedentary fleet seemed to enter and participate in its local port area when revenues exceeded some threshold level. In another study of weekly spatial fishing location choices, Evans (1997) found similar behavior in the California salmon fleet and also found that the mobile fleet was more productive, other things equal, than the sedentary fleet. In a comprehensive study of within-season weekly location choice by East Coast groundfish fishermen, Holland and Sutinen (1999, 2000) conducted tests of spatial behavior using a flexible model of choice employing depictions of expectations and information decay using both short- and long-term expectation processes. Their specification of what kinds of information fishermen focus on is grounded in interviews with fishermen about actual searching behavior. They find similar evidence of a fleet composed of home-port differentiated sub-fleets, some which respond quickly to profit changes and some which are more sluggish. They also find evidence similar to Evans' findings that highliners seem to be more mobile and opportunistic.

A few studies have used panel data on a very fine scale (daily or hourly) to study short-term location and fishing participation choices. In a study of the pink shrimp fishery, Eales and Wilen (1985) show that, in repeated daily decisions, pink shrimp fishermen select patches in a manner consistent with forecasts of mean revenues based on the most recent past prices and catch per unit effort, namely the previous day's data. Shrimp concentrations are ephemeral, and they examine the manner in which fishermen use information sharing groups to expand their spatial search capability in light of the rapid decay of current information. Smith and Wilen (2003) also estimate a model of daily location and participation choice by sea urchin divers, finding that backward-looking moving average expectations mechanisms that span the previous month best predict patch choice behavior. This reflects the more stable nature of price and abundance information in the urchin fishery *vis-à-vis* other fisheries for which the value of specific information decays rapidly. They also explore differences between short-(daily) and longer-term spatial behavior, finding that elasticities of spatial responsiveness increase in the long run as fishermen switch home ports and home regions (Smith and Wilen 2004).

While fine-scale modeling of repeated daily spatial choice behavior allows convenient use of repeated discrete choice econometric models, the specification of trips with longer duration searching and fishing over larger areas is considerably more difficult. Curtis and McConnell (2004) test a multi-day, multi-species targeting model of Pacific longline vessel spatial behavior, using a novel method of depicting the attractiveness of different spatial locations and targeting species simultaneously. They update information and track decisions on a daily basis, including the decision to return to port, which depends upon expected quality decay. They also find strong evidence that spatial patterns of exploitation are responsive to and predicted by relative differences in proxies for expected profits. As a generalization from all of the empirical studies of fishermen behavior, fishermen behave as economic theory suggests, adjusting high fixed costs and relatively inflexible inputs, such as vessel capital sluggishly, while adjusting other flexible inputs such as vessel days and fishing location much more quickly.

The studies of fine-time and spatial-scale behavior raise a number of interesting fundamental questions and research issues. One important and understudied empirical issue is how opportunity costs affect behavior. Opportunity costs are likely to be a key determinant of actual fishermen behavior; yet they are almost always treated as an unobservable lurking behind any empirical behavior analysis. For short-term participation choices, what are the relevant opportunity costs? What kinds of alternative within-season employment opportunities do skippers, crew, and owner/operators have? How do these affect decisions about whether to fish or not? How different are opportunity costs in fishing, and are these differences responsible for the kinds of heterogeneous behavior that we typically witness?

Another important issue relates to heterogeneity in behavior revealed by many empirical analyses. Why do we find mobile and sedentary or generalist and specialist vessels in the same fishery? Does the simultaneous existence reflect heterogeneous fixed or variable costs (McKelvey 1983), or opportunity costs, or skill and experience, or risk attitudes? Why do we see spatially intransitive behavior where some vessels are going from A to B at the same time others are going from B to A? These questions may have simple answers in the sense that they simply reflect empirical specifications that contain important unobservable variables. Alternatively, these kinds of apparent inconsistencies may reflect fundamental but inadequately unexplored structural aspects of fishing behavior. For example, some apparently intransitive or heterogeneous responsiveness may be an artifact of the fact that much of what is treated as fishing behavior by analysts is actually searching behavior. In a stochastic setting, fishermen have both public and private knowledge. Moreover, some knowledge may be long lived, and other information may be ephemeral and decay rapidly. In many fisheries, fishermen spend a great deal of effort probing, sampling, and gathering new information about where to actually set their gear to begin harvesting. Often, fishermen search for fishable patches by trawling or setting gear over likely aggregations or by sharing information in groups. As analysts, we generally cannot differentiate between whether a trip to a location and a subsequent tow is made to fish or to sample the ocean floor. In addition, we don't observe actual *ex ante* expected profits, but must instead use proxies based on what we see *ex post* in the data (Smith 2000). This situation, in which important decision variables affecting spatial behavior are unobservable, poses difficult econometric issues that may only be resolved by more serious ethnographic field work that actually asks fishermen how they form expectations.

Integrated Bioeconomic Policy Modeling

The second important broad area deserving more emphasis by fisheries economists is that of developing and calibrating integrated bioeconomic policy models. Most management modeling is done with purely biological models that employ simplified assumptions about fishing mortality. Most models used by managers, in fact, assume that fishing mortality is fixed and unresponsive to the economic variables that we know cause changes in behavior. An important task is thus helping develop behavioral models of the fishing sector that can be integrated with biological models in order to realistically forecast the effects of policy changes. This is particularly important if we are to successfully understand how finer-scale management might work in practice. We know, for example, that spatial restrictions will alter relative expected profits over space, leading to substitution effects and participation effects. We also know that these kinds of responses are likely to be complicated, with both spatial and temporal dynamics and short- and long-term feedback effects on the biological system. Thus, attempts to model spatial policies with naïve, and *ad hoc* assumptions about fishermen response will likely be far from the mark and cause managers to misestimate the implications of policy options (Wilen *et al*. 2002)

There are the beginnings of some new understanding about how spatially explicit linked bioeconomic systems might be expected to behave. Sanchirico and Wilen (1999) developed a model of spatial and intertemporal effort responsiveness in a patchy metapopulation system under open-access incentives. They show that the kinds of patterns in effort, harvest, and biomass levels that emerge as spatial equilibria depend, to a great extent, on the nature of biological linkages and oceanographic processes that influence a marine system. A wide range of possible configurations of spatial effort distribution is possible, each specifically dependent upon biological dispersal mechanisms and fundamental bioeconomic parameters. Moreover, they show that the dynamics of spatial systems with both biological dispersal and economic arbitrage behavior can be complex and reflective of inherent spatial heterogeneity in biological processes, as well as inherent economic heterogeneity. Additional similar types of conceptual exploration of linked spatially explicit systems are needed to gain fundamental understanding of the manner in which space matters to exploited systems.

In addition to conceptual work in progress, there is only a handful of examples of empirically calibrated, spatially explicit bioeconomic models that do justice to the economic side of the system. An early example is the important work by Holland and Brazee (1996), examining how spatial closures affect a dynamic, spatial system. While their model does not incorporate endogenized responsiveness of effort to spatial closures, it is fully dynamic and shows how spatial policies, such as marine reserves, can have short- and long-term dynamic effects that are complicated and not always intuitive. As they demonstrate, for many difficult fisheries policies that involve lengthy rebuilding phases, the interaction between the biological systems dynamics and the discount rate can be a key determinant of financial feasibility. In more recent empirically calibrated bioeconomic modeling effort, Smith and Wilen (2003) develop, estimate, and calibrate a detailed model that endogenizes effort responsiveness to relative spatial profit changes. They show that the responsiveness of effort to changes in economic incentives is crucial to being able to forecast even the direction of change in important variables before and after policy changes. More modeling that incorporates realistic life cycle properties of populations, distributed over space in ways reflecting spatial mechanisms, and linked up to behavior models of effort will be crucial to understanding and predicting the implication of future spatial policy options.

Policy Design

A third research area that deserves attention of fisheries economists is the broad area of how to design new policies that account for the importance of space in real systems. As argued above, new views about how marine ecosystems are configured over space and how patchy abundance is affected by oceanographic processes raise new questions about how to redesign policy to account for patchiness. If we take as a maintained hypothesis that fish-finding technology will continually improve, and that fishermen will become more responsive and more effective, how should management systems adapt? One option is to simply make conventional systems "more spatial" by subdividing traditional management zones into more and smaller areas, each with its own total allowable catch (TAC), size limits, and effort control measures. But how would one design such a system? At one end of the spectrum is a situation in which the marine environment is managed with a patchwork of location-specific reactive regulations and fishermen are free to move within and among zones. One can imagine, for example, a spatial version of a regulated, open-access system analyzed by Homans and Wilen (1997) in which seasons are closed once the patch TAC target is achieved. But in a spatial setting with connectivity externalities between zones, this would not be optimal since it would not account for linkages between harvest rates over the whole system. At the other end of the spectrum of options is a system of finely specified spatial and temporal property rights that give a limited class of rights holders permission to harvest in particular ways. How might this kind of a system operate? How, in particular, would the level of permitted harvests be determined, and would this be updated over the season? What are the implications of different kinds of transferability, and how are the implications dependent on biological spatial processes linking different patches? These are fundamental questions about which we know little at the moment. Aside from Holland (2004), few have begun to think about the broad implications of property rights structures in a spatially disaggregated marine setting.

A related issue is how to design new management systems in light of newly emerging constituent interests in marine services unrelated to harvest benefits. The past decade has witnessed growing influence on marine policy by environmental lobbyists, supported by marine scientists and funded by philanthropic trusts such as the Pew and Packard Foundations. These new lobbying interests are making strong, convincing cases that parts of the ocean environment ought to be protected from fishing in order to support production of non-consumptive uses and public good ecosystem services. What this means in practical terms is that future management systems must not only address the difficult task of designing new spatial fisheries management systems, but also new systems that manage other services best produced by excluding fishing. There are at least two major research agendas germane to this issue. The first has to do with the nature of these values. While we know that constituents who support non-consumptive service production are passionate, we know little about how the public perceives and values these services. What is the willingness to pay of the average citizen for a network of marine protected areas? Is it the same for the man on the street in Kansas as it is for a coastal resident? How do aggregate values for protecting non-consumptive values compare with consumptive fishery values? The second research area relates to management system design with mixed public and private values and mixed consumptive and non-consumptive services. What kind of spatial system might be used to manage both kinds of services? Would it be best to manage a mixed system with a mix of closed areas and spatially regulated restricted access policies, or would it be best to move directly to clarifying and allocating a system of restricted property rights? If partial rights systems are developed, what are the implications of different degrees of specificity, transferability, and excludability?

Summary and Discussion

The past decade has witnessed an explosion in new information about the relative abundance of marine organisms and the nature of the marine benthic environment. Much of this new information is an indirect product of technology deployed for commercial, military, and weather forecasting purposes. Regardless of original intent, there is now a better understanding of how populations are spatially distributed in marine ecosystems and how concentrations are related to different types of habitat. The most important generalization from intensive monitoring studies is that populations are distributed in clumps or patches rather than homogeneously. This finding of the pervasiveness of patchiness, in turn, has led marine scientists to begin investigating why aggregations are located where they are. These investigations have led to new understanding of the role of intrinsic habitat productivity, oceanographic forces that affect adult and larval transport, inter- and intra-specific competition, and fishing mortality in determining relative abundance.

Perhaps paradoxically, the same technology that has allowed us a clearer understanding of how marine ecosystems operate, has simultaneously increased the vulnerability of these systems by increasing the searching efficiency of the harvesting sector. With new technology, fishermen are more easily able to locate aggregations of sedentary sub-populations and subject them to more focused, prolonged fishing mortality. In addition, the advent of real-time monitoring and data gathering and data processing technology has improved harvesters' ability to locate and quickly move to aggregations of ephemeral pelagic fish. Thus, many populations are more vulnerable to exploitation than when information and understanding was less sophisticated.

The increased searching efficiency of harvesters, brought on by both knowledge and monitoring technology, will surely pose new difficulties to managers charged with protecting fish populations from overfishing. At the same time, managers are facing other added mandates imposed by environmental constituents concerned by a broader suite of marine ecosystem services. These two forces are combining to force changes in the spatial scale and detail over which marine systems are managed. Perhaps most importantly, future fisheries management systems will need to account for resource patchiness and the links between patches, all within a system that also recognizes and addresses non-fishing values, such as biodiversity protection. Future systems will almost certainly include some of the new proposals for permanent and temporary closed areas that we are seeing promoted by marine ecologists and conservation biologists. In addition, we are likely to see fishing managed with temporary closed areas and rotating harvest zones. Lastly, we are also likely to see the gradual conversion of whole population management into zoned fisheries management, probably in three rather than two dimensions. This zoning of the ocean will ultimately morph into an electronically monitored and enforced system of mixed spatial regulations, such as spatial delineated limited entry permits and quota programs, and spatially differentiated gear regulations, size limits, and closed seasons.

This new vision of the future of marine coastal management raises a number of important and interesting research topics that deserve attention by resource economists, fisheries economists, and fisheries scientists. We have highlighted a few, namely: (*i*) better understanding of the determinants of the spatial behavior of fishermen; (*ii*) understanding and predicting how spatial behavior of harvesters combined with spatial population processes interact and determine the character of exploited metapopulations; and (*iii*) understanding the implications of different kinds of policy options, ranging from spatially refined, regulated restricted-access systems, to partial property rights systems granting harvesting and other use rights to marine resources. Several of the papers in this issue touch on these issues and some represent the first attempts at answering what are generally quite complicated questions. These papers clearly just touch the surface of a broad new field of inquiry, but they are also demonstrative of the kind of new fisheries economics research that is needed in order to pave the way toward improved fisheries management systems of the future. Ultimately, new knowledge and understanding of the oceans presents us with new questions, but also with new opportunities to confront and reduce risk and uncertainty and to increase the value generated by renewable resource systems.

References

Beverton, R.J.H., and S.J. Holt. 1957. *On the Dynamics of Exploited Fish Populations*. London, England: Chapman and Hall (reprinted in 1993).

Bjorndal, T., and J. Conrad. 1987. The Dynamics of an Open Access Fishery. *Canadian Journal of Economics* 20:74–85.

Bockstael, N., and J. Opaluch. 1983. Discrete Modeling of Supply Response Under Uncertainty: The Case of the Fishery. *Journal of Environmental Economics and Management* 10:125–37.

Curtis, R., and K. McConnell. 2004. Incorporating Information and Expectations in Fishermen's Spatial Decisions. *Marine Resource Economics* 19(1):131–43.

Eales, J., and J. Wilen. 1985. An Examination of Fishing Location Choice in the Pink Shrimp Fishery. *Marine Resource Economics* 2:331–51.

Evans, M. 1997. *An Analysis of Vessel Performance and Mobility in the California Commercial Salmon Fishery*. Ph.D. Dissertation, University of California, Davis, USA.

Hilborn, R., and M. Ledbetter. 1979. Analysis of the British Columbia Salmon Purse Seine Fleet: Dynamics of Movement. *Journal of the Fisheries Research Board of Canada* 36:384–91.

Holland, D.S. 2004. Spatial Fishery Property Rights and Marine Zoning: A Discussion with Reference to Management of Marine Resources in New England. *Marine Resource Economics* 19(1):21–40.

Holland, D.S., and R.J. Brazee. 1996. Marine Reserves for Fisheries Management. *Marine Resource Economics* 11:157–71.

Holland, D.S., and J.G. Sutinen. 1999. An Empirical Model of Fleet Dynamics in New England Trawl Fisheries. *Canadian Journal of Fisheries and Aquatic Sciences* 56:253–64.

___. 2000. Location Choice in New England Trawl Fisheries: Old Habits Die Hard. *Land Economics* 76(1):133–49.

Homans, F., and J. Wilen. 1997. A Model of Regulated Open Access Resource Use. *Journal of Environmental Economics and Management* 32:1–21.

Lane, D. 1988. Investment Decision Making by Fishermen. *Canadian Journal of Fisheries and Aquatic Sciences* 45:782–96.

McKelvey, R. 1983. The Fishery in a Fluctuating Environment: Coexistence of Specialist and Generalist Vessels in a Multipurpose Fleet. *Journal of Environmental Economics and Management* 10(4):287–309.

Ricker, W.E. 1954. Stock and Recruitment. *Journal of the Fisheries Research Board of Canada* 11:559–623.

Sanchirico, J.N., and J.E. Wilen. 1999. Bioeconomics of Spatial Exploitation in a Patchy Environment. *Journal of Environmental Economics and Management* 37:129–50.

Smith, M.D. 2000. Spatial Search and Fishing Location Choice: Methodological Challenges of Empirical Modeling. *American Journal of Agricultural Economics* 82(5):1198–206 .

Smith, M.D., and J. Wilen. 2003. Economic Implications of Marine Reserves: The Importance of Spatial Behavior. *Journal of Environmental Economics and Management* 46:183–206.

___. 2004. Marine Reserves with Endogenous Ports: Empirical Bioeconomics of the California Sea Urchin Fishery. *Marine Resource Economics* 19(1):85–112.

Wilen, J. 1976. *Open Access and the Dynamics of Overexploitation: The Case of the North Pacific Fur Seal*. UBC Natural Resource Economics Working Paper No. 3., Department of Economics, University of British Columbia. Vancouver, British Columbia, Canada.

Wilen, J.E., M.D. Smith, D. Lockwood, and L.W. Botsford. 2002. Avoiding Surprises: Incorporating Fishermen Behavior into Management Models. *Bulletin of Marine Science* 70(2):553–75.